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# Contextualising adaptive comfort behaviour within low-income housing of Mumbai, India

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## Abstract

Thermal adaptation in low-income housing of Mumbai, India is investigated using a longitudinal field study and in-situ field measurements. 705 set of responses from two different neighbourhoods were analysed to understand the patterns of behavioural adaptation. Spatial configuration, temporal factors and underlying societal norms influenced the comfort-related behaviour in low-income housing. Clothing adaptation was primarily governed by the gendered socio-cultural practice of *purdah* system and western influences rather than thermal needs. Logistic regression predicts probabilities of 88% and 20% for using ceiling fans and exhaust fans respectively at 80% indoor air relative humidity. However, thermal stimuli cannot predict occupant behaviour well due to presence of non-thermal determinants. Security, privacy, environmental nuisances (dust, noise and odour) and insects or animals menace (mosquitoes, monkeys, rats, lizards) were the major barriers to thermal adaptation. The study is helpful in evaluating the influence of occupant behaviour on building performance and thus to inform building design and operation. The policy implications could be through the development of design guidelines for the housing schemes to create thermally comfortable low-income dwellings.

**Keywords:** occupant behaviour, low-income housing, adaptive behaviour, thermal adaptation, environmental controls.

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***Abbreviations***

| | |
|---|---|
| LIG | Low-income Group |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| ISO | International Standard Organization |
| °C | Degree Celsius |
| $T_{out}$ (°C) | Outdoor Temperature |
| $I_{cl}$ (clo) | Clothing insulation |
| $Rh_{out}$ (%) | Outdoor Air Relative Humidity |
| $T_g$ (°C) | Globe Temperature |
| $T_{air}$ (°C) | Air Temperature |
| $T_{mrt}$ (°C) | Mean radiant Temperature |
| $T_{op}$ (°C) | Operative Temperature |
| $Rh$ | Relative Humidity |
| $V_a$ (m/s) | Air Velocity |
| L (lux) | Lux Level |

***Nomenclature***

| | |
|---|---|
| *PropWin* | Proportion of windows open |
| *PropDoor* | Proportion of external doors open |
| *Propcf* | Proportion of ceiling fan in use |
| *Propef* | Proportion of exhaust fan in use |
| *Propcurt* | Proportion of curtains open |
| *Proplt* | Proportion of use of lights |
| *pwin* | Probability of opening windows |
| *pcf* | Probability of using ceiling fans |
| *pef* | Probability of using exhaust fans |
| *pcurt* | Probability of drawing curtains |

# 1 Introduction

Residential sector consuming 22% of global energy has a substantial role in mitigating global climate change [1]. The human factor, that includes occupant choices and behaviour in buildings, is critical in understanding one-third of the energy consumption residential sector [2]. In thermal comfort realm, the knowledge on how occupants adapt to their environment is central to understanding the demand side energy management. In Indian context, rapid urbanization and rural-urban migration would force the future urbanites to live in social housing due to economic challenges. Further, the movement of providing affordable housing has created a new typology of building. In Mumbai, where more than 50% of population lives in low-income housing, this archetype of residential units will prevail. Apparently, the socio-economic conditions of the low-income occupants dictate their thermal comfort behaviour [3]. Growing consumption and its associated influence on global resources and environmental challenges, as well as rapid technology transition can also drive a significant change in behaviour. Moreover, characteristics of the built environment may also promote changes in occupant behaviour and adaptation processes [4]. The multifaceted behaviour of the low-income population, which are a vital cohort in the rapidly urbanising world due to the energy demand and energy security issues, is an important topic of research and demands further attention.

The centrality of behavioural adaptation in determining building energy use and comfort levels necessitates a deeper investigation of occupants' adaptation to their thermal environment. This study, a first-of-its-kind to characterise occupant behaviour in low-income housing in India, involves measuring and monitoring the indoor thermal environment of such housing through an extensive field study approach. With a broader goal of developing a better understanding of thermal behaviour of low-income dwellers, the work aims at addressing the following objectives using Mumbai as a case study.

- To understand the patterns of behavioural adaptation for improving comfort in low-income housing in India.
- To explore the non-thermal determinants of adaptive comfort behaviour.
- To quantify comfort-related occupant behaviour involving the use of environmental controls.
- To inform solutions and strategies to improve thermal environment of low-income housing.

Occupants adapt to the indoor thermal environment by engaging in adaptive actions to match their thermal preferences. Brager and de Dear emphasize that "*thermal preference is affected by circumstances beyond the physics of the body's heat balance, such as climatic setting, social conditioning, economic consideration and other contextual factors*"[5]. It is therefore important to consider the causes and effects of non-thermal factors such as socio-cultural, economic and contextual settings in conjunction with the indoor environmental variables on the adaptive comfort behaviour.

Literature on residential comfort behaviour is predominately focused on mixed mode buildings where occupants majorly rely on energy-intensive space conditioning devices for improving their indoor thermal environment. Hwang et al. found that thermal adaptation behaviour within Taiwanese homes is affected by convenience in use and affordability of the adaptation methods to achieve thermal comfort [6]. Similar inferences were drawn by Indraganti and Uno et al. for Indian and Indonesian residences respectively [7,8]. Kim et al. [9] concluded from their Australian residential study that the availability of adaptive strategies and occupant's attitude affected the decision of using air conditioners (ACs) whereas Song et al. concluded education and income to be the significant factors affecting such decisions in Chinese households [10]. Other factors such as privacy, time of the day, efficacy of controls were also found to be significant in relation to the adaptive use of environmental controls within mixed mode residential buildings [7,11].

In contrast, there exists limited literature on thermal behaviour within naturally ventilated housing, particularly occupied by low-income groups (LIG), where the issue of thermal comfort is reduced to be an issue of unavoidable acceptance because of the lack of affordability of space heating or cooling equipment [12]. Sanchez et al. [13] and Moore et al. [14] found that occupants of low-income households prefer a combination of passive thermal strategies such as turning on ceiling fans, opening or closing windows and doors, opening or closing curtain, along with clothing and activity adjustments. Additionally, Pérez-Fargallo et al. [15] pointed out that LIG occupants lower their thermal expectations due to fuel poverty and thus reflect an unfamiliar comfort behaviour. The scant literature within LIG households focuses merely on economic affordability with no regard to other non-thermal factors (socio-cultural or contextual). A comprehensive understanding of occupant behaviour within low-income housing, which remains decoupled from the socio-economics in the existing literature, is thus required. This knowledge gap is addressed here by investigating the patterns of adaptive comfort behaviour within LIG housing and analyzing the related non-thermal triggers and drivers.

## 2 Study area & methods

Mumbai is the capital city of Maharashtra located in the western seaboard of India. The city spans a total area of 603.4 square kilometers with an average elevation of 14 meters [16]. The coastal city, characterized by a mean monthly maximum temperature above 25 °C and relative humidity above 75% [17], falls within the warm humid zone under the National Building Code of India. Annual meteorological data (2019) for the city of Mumbai has been presented in Figure 1. This study is based on the field survey conducted in the monsoon (August and September), winter (January) and summer (May) months which are representative of the different climatic conditions of Mumbai and helps in capturing the seasonal variation of thermal comfort behaviour.

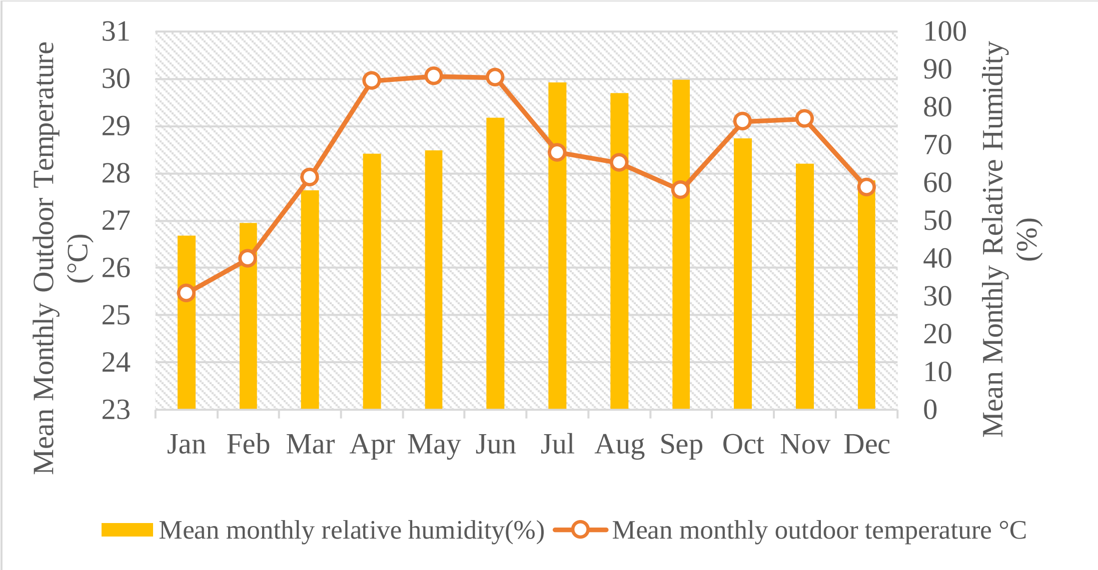


Figure 1: Mean monthly temperature and humidity for Mumbai (Year 2019) [18]

Low-income group [1] (LIG) housing, particularly in Mumbai, are considered as thermally uncomfortable with poor indoor air quality [3,19]. Additionally, the energy cost burden of such housing is estimated to be as high as 25% [20]. Mumbai's LIG housing archetypes comprise of *chawls,* slum rehabilitation housing (SRH) and government staff housing. While *chawls* form the traditional low-income housing, the SRH or the government staff housing typologies represent the future affordable housing stock [20–22]. Thus, the Mumbai's LIG housing consisting of SRH and government employee housing was chosen as the study area.

## 2.1 Description of buildings

Two urban low-income housing neighbourhoods were selected for the field study. The first neighbourhood is a slum rehabilitation housing complex located in Ward M, Mumbai comprising of identical high-rise towers. The residents comprise of slum dwellers' families which have been shifted to this vertical housing as a part of State government's Slum Rehabilitation Scheme [23]. The hyper dense, eight-storey structures have twelve single-roomed dwellings of 22 square meters

[1] Low income group are defined as households having an annual income between INR 300,001 up to INR.600,000 i.e. USD 4200 to 8400 (1 USD=71.2 INR).[49]

each on every floor. Each studio unit consists of a multipurpose hall, a kitchen area and an attached toilet facility (See Appendix A). The second neighbourhood located in Ward S, Mumbai is situated within the lush green institute campus of Mumbai and comprises of three-storey buildings with different spatial configurations. These buildings are typically occupied by families of administrative staff employed by the institute. The dwelling size ranges between 26 square meters to 32 square meters comprising of one or two rooms, a dedicated kitchen area, and bathing facility. The spatial configuration of the housing units is attached in Appendix A while the neighbourhood characteristics are depicted in Figure 2. For the rest part of this paper, the two locations- Slum rehabilitation colony and institutional campus housing are referred as Location 1 (L1) and Location 2 (L2), respectively.

All the surveyed buildings are uninsulated reinforced concrete (RCC) frame structures with in-fill brick wall construction. The housing units have operable windows with either naturally ventilated or mixed mode operation. However, during the time of survey, all the units were operated in free-running mode (i.e. without any mechanical cooling). Apart from the two buildings from L2 with RCC pitched roof, all the other buildings had RCC flat roofs.


Figure 2: Glimpses of surveyed neighbourhoods.

## 2.2 Survey Protocol

Longitudinal field surveys were administered in the low-income housing neighbourhoods for 20 days across the year using a combination of random stratified sampling and snowball sampling to select the respondents. Best possible effort was made to ensure a heterogeneous representation of samples with respect to age, gender, location and time of the day. Each respondent was surveyed three times a day from 10 am to 9 pm with an interval of at least 2 hours between the consecutive observations.

The survey comprised of five components: socio-demographic details, subjective thermal comfort & comfort acceptability votes, personal comfort variables, environmental controls and in-situ measurement of indoor environmental parameters as described in Table 1. A deeper insight to behavioural adaptation was gathered by enquiring about the associated socio-cultural, contextual or economic constraints with the use of environmental controls. In addition to the longitudinal survey, built form characteristics in form of floor plans, interior features, building materials, housing conditions and site surroundings were collected.

Table 1: Questionnaire survey and related description

| Survey Components | Description | Remarks |
|---|---|---|
| Socio-demographic details | Age, gender, height, weight, years of residency, housing unit location and appliance ownership | Appliance ownership gathered as binary data: 0 in unavailable, 1 if available. |
| Subjective thermal comfort | Thermal sensation, preference and acceptance. | Not within the scope of this paper. |
| Personal comfort variables | Clothing insulation and metabolic activity in past 15 mins | Clothing insulation ($I_{cl}$) checklist adopted from ASHRAE [24] and Indian field studies (See Appendix B). Metabolic rates identified from ISO 8996 [25]. |
| Environmental controls: availability, usage and constraints | Natural ventilation controls (windows, external doors, balcony doors); electro-mechanical controls (ceiling fan, exhaust fans, air-conditioners) and others (curtains, artificial lights) | Availability and usage gathered as binary data: 0 if unavailable or not in use or and, 1 if available or in use. |
| Measurement of indoor environmental parameters | Air temperature, globe temperature, relative humidity, air velocity and illuminance levels. | The instrumental setup comprised of Testo 480 meter, IAQ probe, globe thermometer, vane probe and lux probe [26] |

The immediate thermal environment was measured following Class II field study categorization recommended by ASHRAE [24]. Figure 3 depicts the typical survey settings and instrumental setup. Table 2 provides the specifications of the digital hand-held instruments used for recording the concurrent environment parameters.


Figure 3: Field survey setting and Testo 480 instrumental setup

Table 2: Specifications of the measuring instruments [26]

| Instrument | Parameter measured | Range | Resolution | Accuracy |
|---|---|---|---|---|
| Testo 480 IAQ probe | Air Temperature | 0 to 50 °C | 0.1°C | ±0.5 °C |
| | Relative Humidity | 0 to 100 %RH | 0.1% RH | ±(1.8%RH + 0.7% of mv) |
| Globe thermometer (150mm) | Globe Temperature | 0 to 120 °C | 0.1°C | Class 1 (EN 60584-2) |
| Vane probe (Ø 100 mm) | Air velocity | 0.1 to 15 m/s | 0.01 m/s | ±(0.1 m/s + 1.5 % of mv) |
| Testo 480 lux probe | Lux level | 0 to 100000 Lux | I lux | Class C (DIN 5032-7) |

*mv= measured value*

# 3 Survey Results

## 3.1 Sample size distribution

A total of 107 respondents across the three phases of longitudinal survey were interviewed to gather 705 set of responses. The number of respondents varied in each phase since some of them were either unavailable or unwilling to participate. Figure 4 illustrates the descriptive statistics of the respondents with respect to age, gender, years for residency and household appliance ownership.

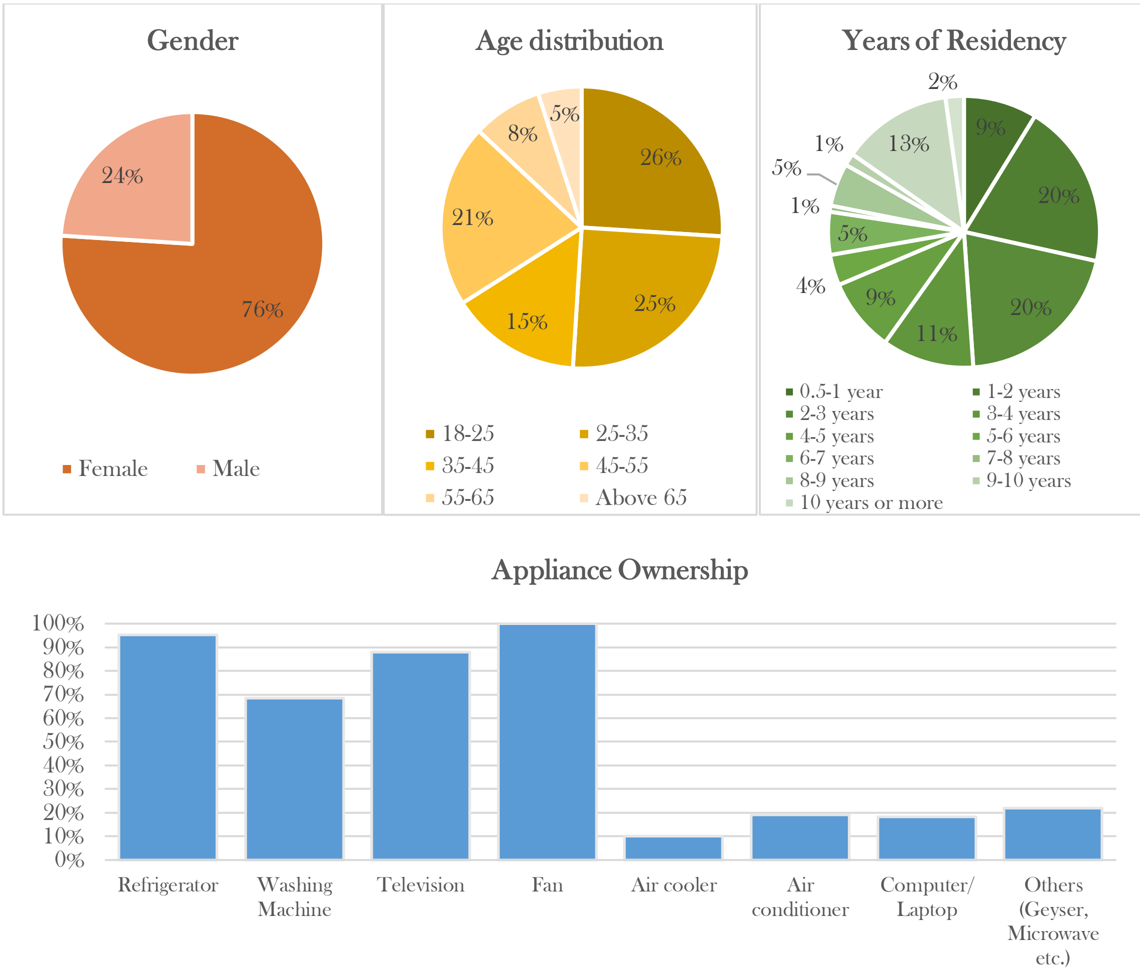


Figure 4: Sample size distribution.

About 76% of the respondents were female and 24% were the males. The larger share of females was attributed to a larger availability of females within the housing units than the male counterparts. 26% of the respondents were young adults falling within the age group of 18-25 years while another 25% represented the age group of 25-35 years. Other age groups of 35-45 years, 45-55 years and 55-65 years constituted to 15%, 21% and 8% of the samples respectively. A small percentage (5%) of samples were above the age of 65 years.

About 51% of respondents were residing in the housing unit for more than 3 years while about 9% of the respondents had a short period of residency of less than a year. Occupants staying for less than 6 months were excluded from the field survey since they may not be fully aware of the adaptive opportunities present in their indoor environment.

Refrigerators, televisions and washing machines were found to be the common household appliances with an ownership of 94%, 86% and 70% respectively. Ceiling fans were present in all the households but space cooling equipment- air-conditioners and evaporative coolers had a limited ownership of 17% and 12% respectively. Laptops or computers were owned by 18% of the households while the other appliances such as geysers, microwaves, etc. had a cumulative ownership of 21%.

### 3.2 Outdoor and indoor environmental conditions

Outdoor environmental data comprising of daily mean temperature and relative humidity were gathered through Weather Underground [18] as shown in Table 3. The data were recorded from the nearest weather stations positioned 14 kms and 1 km away from Location 1 and Location 2 respectively. Daily mean outdoor temperature, $T_{out}$ (°C) was in range of 23.1°C to 31.4°C with a standard deviation of 2.5°C. The humidity levels had a wide variation across the seasons with daily mean relative humidity $Rh_{out}$ (%) ranging from 39.0% to 86.3% with a standard deviation of 14.3%.

Table 3: Summary of outdoor environmental variables.

| | Outdoor Temperature (°C) | | | Outdoor Relative Humidity (%) | | |
|---|---|---|---|---|---|---|
| Season | Mean | Minimum | Maximum | Mean | Minimum | Maximum |
| Monsoon | 26.1 | 24.3 | 28.2 | 82.2 | 76.6 | 86.3 |
| Winter | 24.9 | 23.1 | 27.4 | 51.4 | 39.0 | 66.7 |
| Summer | 29.7 | 29.1 | 31.4 | 69.0 | 75.4 | 66.7 |

A summary of indoor environmental parameters has been presented in Table 4. Indoor air temperature, globe temperature, relative humidity, air velocity and illuminance levels were logged during the survey, while mean radiant temperature and operative temperature were calculated as per the standard equations [24,27].

Table 4: Summary of indoor environmental variables recorded.

| Variable | Mean | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|
| Air temperature $T_{air}$ (°C) | 28.6 | 24.2 | 34.2 | 1.9 |
| Globe Temperature, $T_g$ (°C) | 28.9 | 24.8 | 33.8 | 2.0 |
| Mean Radiant Temperature, $T_{mrt}$ (°C) | 29.1 | 22.4 | 36.6 | 2.5 |
| Operative Temperature, $T_{op}$ (°C) | 28.8 | 24.8 | 33.8 | 2.0 |
| Indoor Relative Humidity, $Rh_{in}$ | 64.5 | 39.3 | 87.4 | 13.0 |
| Air velocity $V_a$ (m/s) | 0.3 | 0.0 | 2.9 | 0.4 |
| Illuminance level (lux) | 56.5 | 1.0 | 347.0 | 46.7 |

### 3.3 Environmental controls

Occupants residing in low-income colonies of Mumbai adapt to their thermal environment through the use of natural ventilation controls (doors and windows), mechanical controls (ceiling fans, exhaust fans, evaporative coolers and air conditioners) and other controls (lights and curtains). All housing units are equipped with operable windows, ceiling fans and artificial lighting controls, however, exhaust fans, air-conditioners or evaporative coolers is only available to a fraction of samples. Curtains and balcony doors are restricted to almost half of the housing units surveyed. The availability and usage of environmental controls at the time of survey across 705 responses have been summarised in Table 5. No instances of air-conditioner use were reported at the time of survey while evaporative coolers were operational for 1% of the observations.

Table 5: Summary of environmental controls.

| Natural ventilation controls | Availability (n=705) | Open | Closed |
|---|---|---|---|
| Window | 100% | 60% | 40% |
| Door | 100% | 80% | 20% |
| Balcony Door | 52% | 24% | 28% |
| Curtains | 52% | 24% | 28% |
| **Mechanical controls** | **Availability (n=705)** | **In use** | |
| Ceiling Fan | 100% | 63% | |
| Exhaust Fan | 33% | 3% | |
| Air-conditioner | 9% | 0% | |
| Evaporative cooler | 7% | 1% | |
| **Others controls** | **Availability (n=705)** | **on/up** | **off/down** |
| Artificial lights | 100% | 71% | 29% |
| Curtains | 52% | 24% | 28% |

# 4 Analysis

## 4.1 Adaptation through the use of environmental controls

Thermal comfort in naturally ventilated buildings is affected by the "adaptive opportunity" available to the occupants. "Adaptive opportunity" is generally interpreted as the ability to open a window, draw a curtain, use a fan and so on, and reflects the potential extent to which the current thermal environment can be changed [28,29]. This section examines the influence of thermal stimuli i.e. temperature or humidity on occupants' adaptive actions for improving their comfort levels. Outdoor temperature, indoor globe temperature and relative humidity were binned using equal-width partitioning method at 1˚C and 10% humidity increments to transform continuous data into discrete values. Binning method was helpful in discovering patterns of environmental controls without compromising much on the frequency distribution of bins since the collected data comprise of diverse ranges of temperature and humidity. The bin widths are kept small to minimize the loss of information while keeping in mind the physical significance of the change in bin width on thermal environment. Further, previous studies have also adopted similar intervals which would facilitate the comparative analysis of occupant behaviour.

*Natural ventilation controls: Windows and external doors*

Occupants of naturally ventilated buildings often engage in opening of windows or doors to improve their indoor thermal environment. Figure 5 illustrates the proportion of opening windows and doors with changes in thermal environment variables (outdoor, indoor temperature and indoor humidity) within the surveyed households. Quadratic function was found to be the best fitting relationship for explaining the use of natural ventilation controls and is in agreement with the existing literature. The rationale for the occurrence of this trend is that as indoor temperature or humidity increase, occupants open windows or doors until a certain threshold point which is in equilibrium with the outdoor conditions, and beyond that occupants close the natural ventilation controls to cut off excessive heat and humidity.

Fig 5a) and 5b) depict the *PropWin* in relation to outdoor ($T_{out}$) and indoor globe temperature ($T_g$) and reveals that the highest proportion of windows open at Tout equal to 26°C. The analysis of indoor relative humidity, *Rh* with *PropWin* presented in Figure 5c yielded a stronger quadratic relationship with a higher coefficient of determination ($R_2$=0.90). Additionally, *PropWin* never exceeded above 70% indicating occupants may have been engaging in other adaptive actions over window opening.

Next, the relationship between proportion of external doors open *(PropDoor)* and thermal variables was investigated. It is important to note that external doors may also be operated for non-thermal purposes such as function or security. Thus, relating thermal stimuli with *PropDoor* may not yield strong associations. *PropDoor* and Tout had a reverse quadratic relationship as compared to *PropWin* with a lower $R_2$ value as illustrated in Figure 5a. *PropDoor* with changes in $T_g$ yielded a similar curve as *Propwin* with a comparable $R_2$ value of 0.62. However, *PropDoor* curve was flatter than *Propwin* (Fig. 5b) indicating lower sensitivity of door opening to changes in indoor globe temperature. *Rh* yielded a strong and significant association with *PropDoor* with an increase in proportion of doors open as *Rh* levels increased from 70% to 90% (Fig. 5c). A deeper investigation of *Propdoor* would be carried out in the subsequent subsection by addressing the non-thermal factors affecting the use. Balcony doors were present only in L2 and most of the households had converted the balcony area into an additional room. Hence, due to a smaller sample size, no particular relationship was observed for balcony door opening with thermal environmental variables.

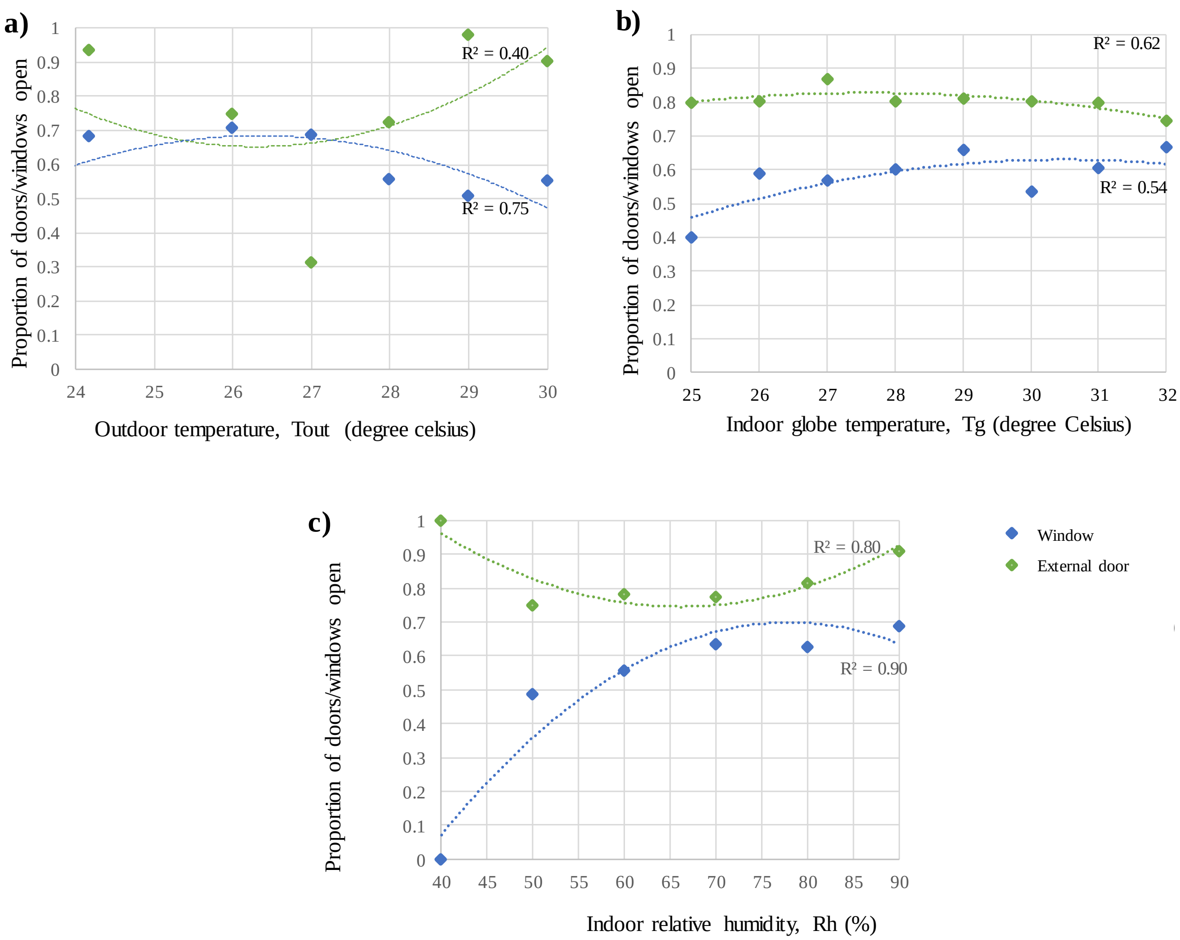


Figure 5: Distribution of proportion of windows and doors open with thermal environmental variables.

*Electro-mechanical controls: ceiling fans and exhaust fans*

Low-energy mechanical devices such as ceiling fans and exhaust fans were adopted by the occupants to increase air flow velocity and reduce indoor temperature thus ameliorating comfort. Ceiling fans are particularly helpful in hot and humid conditions since they increase the air velocity and allowing an increase of up to 3oC in comfort temperature. Exhaust fans, on the other hand, reduce indoor temperature and increase airflow velocity and are proven to be effective in improving thermal comfort within low-income dwellings [3].

Ceiling fan usage was correlated significantly with indoor globe temperature, $T_g$ (r= 0.40) and indoor relative humidity, *Rh* (r=0.50). Proportion of ceiling fan usage *(Propcf)* had a steep upward trend w.r.t $T_g$ and *Rh*, indicating high sensitivity to indoor environment variables (Fig. 6a). Occupants turned on the ceiling fans at globe temperatures above 26°C and about 95% of ceiling fans in use at 32$_o$C. A similar but sharper curve was observed for *Propcf* with changes in relative humidity and 50% fans were in use at 60% *Rh* level. A large *Propcf* at high temperature and humidity levels is possibly due to minimal associated constraints with ceiling fan operations. Exhaust fans usage followed a horizontal curve with indoor temperature with no substantial correlation (Fig. 7a). This could be attributed to preference of other adaptive actions such as ceiling fans or windows at high temperature. Exhaust fan usage correlated significantly with *Rh* (r=0. 26) and a gradual increase in proportion of use *(Propef)* was observed as the *Rh* levels increased from 50% to 90 % (Fig. 7b).

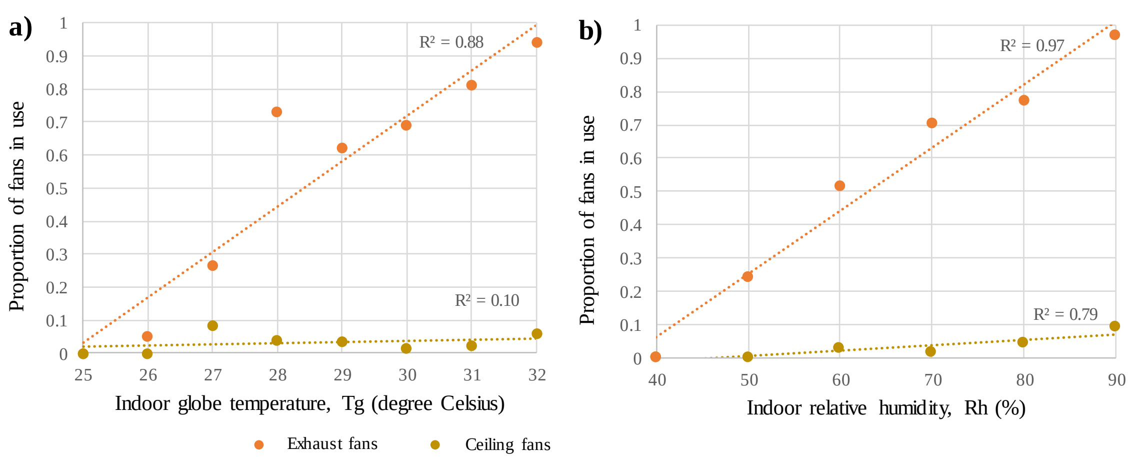


Figure 6: Distribution of the proportion of ceiling fans and exhaust fans in use with thermal environmental variables.

*Other environmental controls: Curtains and artificial lights*

Occupants often engage in adaptive use of blinds/curtains to control solar glare and radiation particularly for reducing indoor temperature. However, non-thermal factors such as privacy can also be a major factor affecting the actions on curtains which has been discussed in the latter part of this paper. Opening of curtains was significantly correlated with indoor (r=0.15) and outdoor temperature (r=0.11) which supports evidence from Nicol 2001 [30]. Figure 7 illustrates the proportion of curtain open *(Propcurt)* at different time of the day and informs that *Propcurt* follows a moderate curve indicating not much variation with time of the day. Literature also points out at the significant relationship of the use of blinds and external illuminance [31] but unfortunately, no such investigation could be carried out due to the non-availability of external illuminance data.

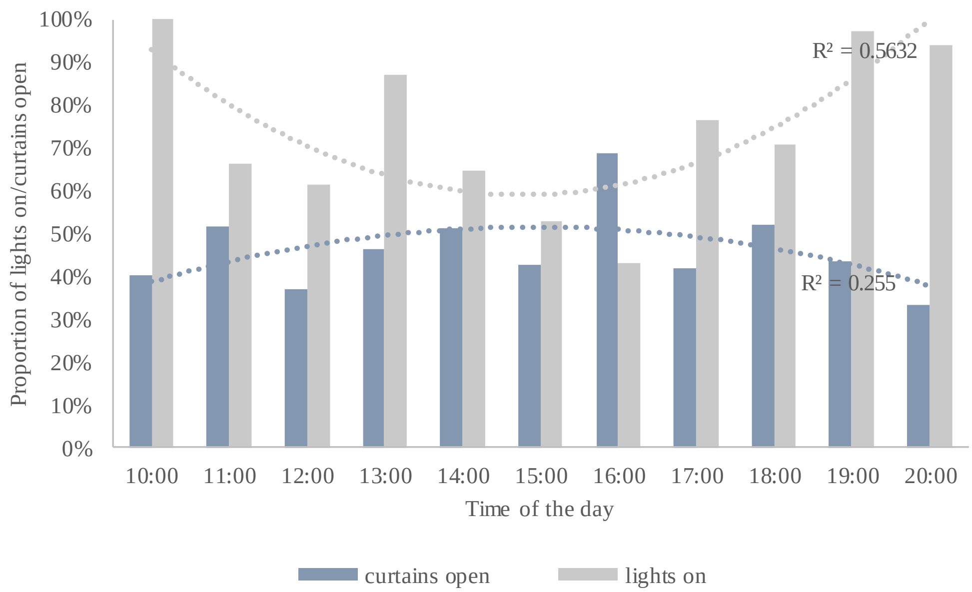


Figure 7: Distribution of proportion of curtains open and lights in use with time of the day.

Drawing curtains to reduce thermal discomfort may result in low indoor lighting levels and in turn trigger the use of artificial lights. Other factors such as indoor temperature, sky conditions and activity type may also affect the use of artificial lights. The analysis of lighting usage revealed correlation with indoor globe temperature $T_g$ (r=0.11) supporting the findings from Indraganti [7] while contradicting those drawn by Raja et al [32]. Proportion of use of lights *(Proplt)* relating to time of the day revealed that artificial lights were used throughout the day but the usage was least in late afternoon hours (3:00 p.m. to 5:00 p.m.) (see Fig. 7). Additionally, the comparison of

*Propcurt* and *Proplt* curves indicate an inverse quadratic trend however it is difficult to identify the cause and effect among the two controls. Indoor illuminance levels were then analyzed in regard to time of the day and the resultant graph has been depicted in Figure 8. The graph indicates that even though artificial lights were in use for 70% of observation time, the lux levels were still below the prescribed ranges (120 to 300 lux) [33] for most of the time. This might be attributed to inefficient luminaires or poor lighting position within the housing units.

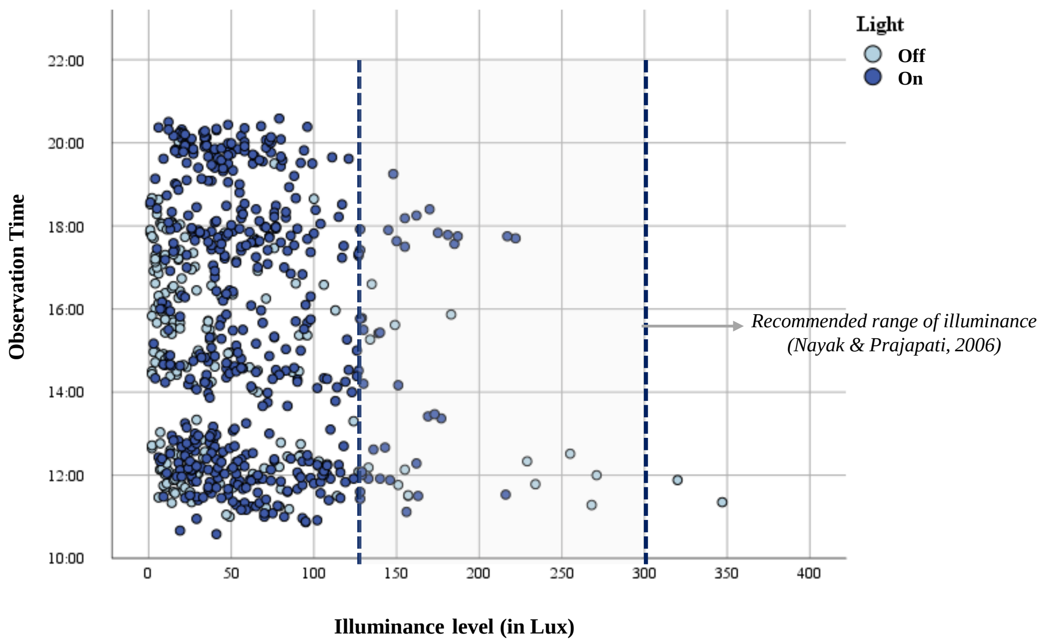


Figure 8: Indoor illuminance in relation to time of the day.

## 4.2 Seasonal and contextual variation

This section draws light upon the seasonal and contextual variation in the adaptive use of environmental controls within LIG housing. The three seasons included in the analysis are monsoon, winter and summer and the corresponding outdoor conditions are explained in Section 2. Figure 9 depicts the differences in the adaptive use of environmental controls viz windows, doors, ceiling fans, exhaust fans, curtains and artificial lights across the three seasons. The percentage of windows open was highest in monsoon season (68%) followed by summer (63%) and winters (49%). This trend was attributed to the effectiveness of windows in reducing indoor temperature and humidity. There were no striking differences in the use of external doors across seasons which supports our supposition that external doors usage may have been dictated by non-thermal functions. Ceiling fans had comparable usage in monsoon and summer months because of their effectiveness in hot and humid conditions whereas in winter months, ceiling fan usage was restricted to 20% due to moderate temperatures and humidity levels. Exhaust fans having limited ownership, were operated mostly in monsoon season (19%) to eliminate high humidity followed by summer season (9%). No instances of exhaust fan usage were reported in winter months. Monsoon season observed highest use of artificial lights because of overcast sky conditions resulting in low indoor illuminance. Summer and winter season had comparable lighting usage despite differences in use of curtains and windows indicating occupants' indifferent behaviour towards lights.

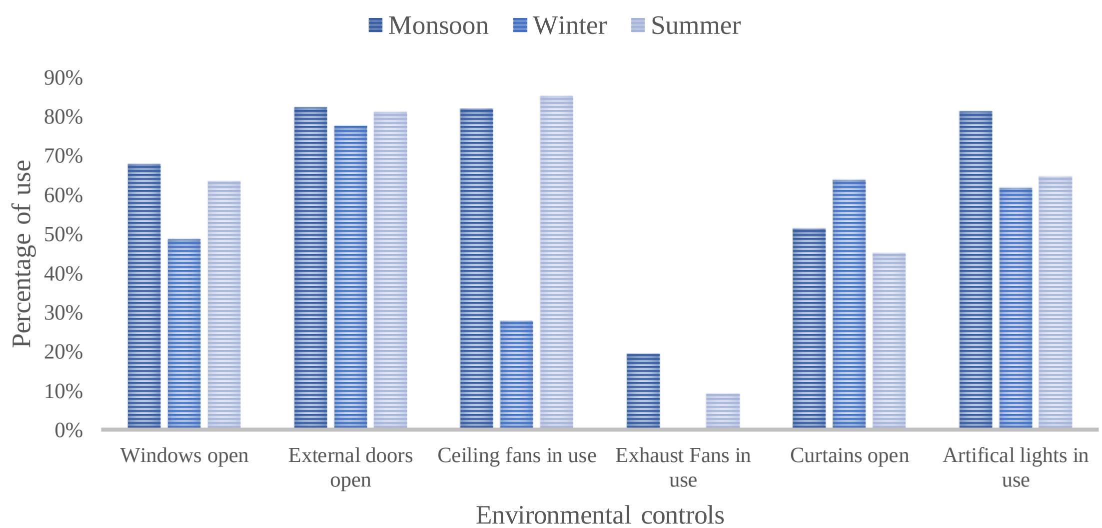


Figure 9: Seasonal variation in the adoption of environmental controls.

Stark differences in spatial layout, built form characteristics and urban setting among the field study locations necessitated the investigation of contextual variation in adaptive occupant behaviour. The contextual variation in use of environmental controls has been presented in Figure 10. There was a higher percentage of external doors kept open and higher usage of exhaust fans and lights in L1 (94%) as compared to L2 (67%). This was attributed to the dense built form and spatial configuration (see Appendix A) of L1 which did not allow cross ventilation and adequate daylight to penetrate into the housing units and in response to the poor indoor environment, occupants adapted to their thermal environment through the use of environmental controls. On the contrary, L2 occupants had adequate provision for cross ventilation and the lush green urban setting facilitated airflow movement across the housing units. Besides, low building heights and wide inter building distance aided in improving indoor environment. The percentage of curtain open was also lower in L1, possibly because of higher use of artificial lights in the densely packed units. Ceiling fan usage was slightly lower in L2 than L1 which could be a result of a cooler microclimate due to the effect of low density green urban setting. No considerable variations were observed in window usage among the two locations.

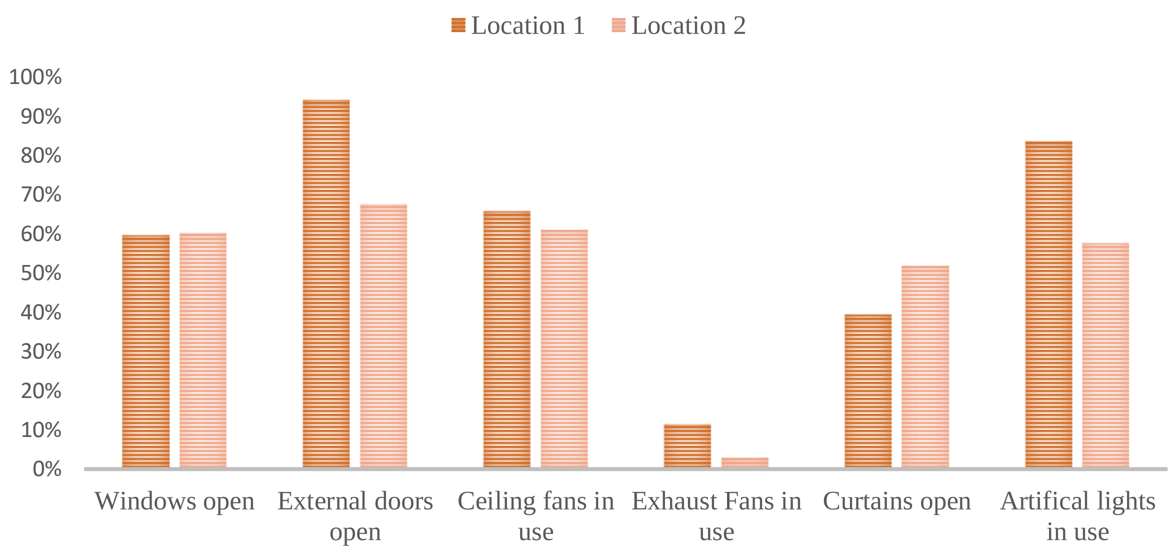


Figure 10: Contextual variation in the adoption of environmental controls.

### 4.3 Adaptation though personal adjustment: Clothing behaviour

LIG occupants were typically dressed in Indian ensembles such as saree, salwar kameez, and lungi (see Fig. 11). A few females covered their heads as a part of religious *purdah* system to show reverence toward men and older women in the family [34] . Western outfits such as T-shirts and denims/shorts or shirt and pants were more common among the male population. Figure 11 depicts the different clothing attire worn by the respondents at the time of field survey. Clothing insulation

($I_{cl}$) correlated weakly with indoor relative humidity (r=-0.40) and outdoor relative humidity (r=-0.14) and had no significant correlation with temperature variables or metabolic rates. A few studies conducted in hot climates also reported poor or no correlation between temperature and clothing insulation [35,36]. It indicates the dominance of non-thermal factors such as socio-cultural controls, attitudes or lifestyle practices in determining the clothing behaviour.


Figure 11: Different clothing ensembles worn by the respondents (Source: Authors).

$I_{cl}$ values ranged from 0.15 to 2.65 clo with a mean value of 0.63 clo across the three seasons. Male respondents have a marginally higher clothing insulation (mean= 0.69, range= 0.15 to 2.65) than the female respondents (mean=0.61, range=0.29 to 2.28) indicating differences in adaptation. The seasonal variation of clothing insulation witnessed slight differences in the mean $I_{cl}$ values (monsoon=0.58, winter=0.61 and summer=0.73). Relatively higher mean $I_{cl}$ values in summer season was examined by plotting the gender and seasonal distribution of clothing insulation as presented in Figure 12. The analysis indicates an unusual pattern of high clothing insulation in summer seasons by a few respondents. Thus, it was deceptive to use the mean $I_{cl}$ values for analysis. The graph also reveals stark gender differences in clothing behaviour across the seasons. In monsoon and summer months, men had a wider band of clothing insulation as compared to females where as in winter season, females adopted relatively higher level of clothing insulation. The occurrences of high clothing insulation particularly in summer season were examined by studying the combined effect of age and gender.

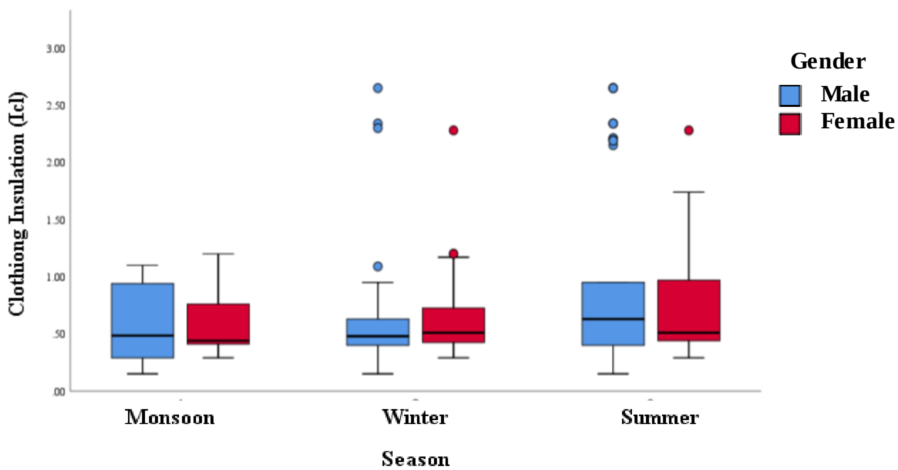


Figure 12: Seasonal and gender variation of clothing insulation.

Figure 13 revealed interesting insights about clothing choices of LIG occupants with respect to age. The young adults (16-35 years), in a desire to be fashionable and reflect modernity through clothing, chose to wear high clothing insulation outfits in hot and humid summer season. This set of population wore apparels such as denim jeans/jackets in tandem with the usage of environmental controls to increase air velocity and improve thermal comfort. Similar inferences were gathered by Indraganti in higher income residential apartments of Hyderabad, India [4]. Gender differences in "adaptive saturation" [37] of clothing can also be observed from Figure 13. For instance, men exercised the adaptive clothing opportunity in high summer temperatures by wearing *lungi*, whilst the female counterparts wore a cotton sari or long gown.

Men had a lower "adaptive saturation" level (0.15) while females have a slightly higher (0.29) which was attributed to the underlying socio-cultural regimes dictating minimal socially acceptable limit for clothing. This trend is supported by the previous field studies conducted in Indian context.

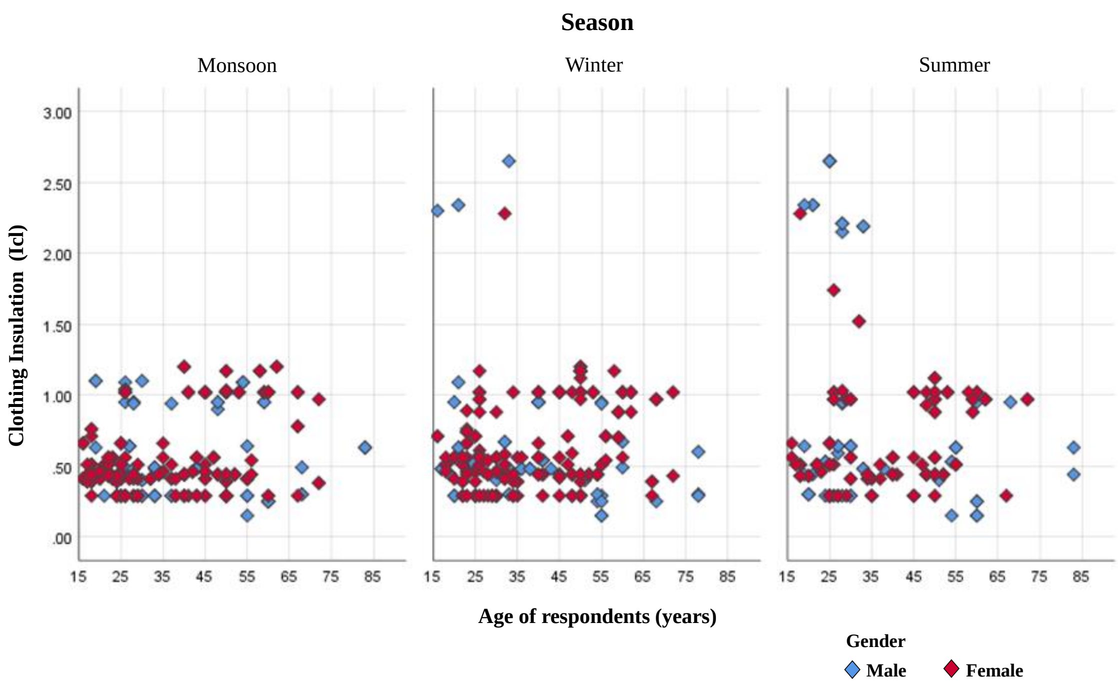


Figure 13: Seasonal trends of clothing insulation with respect to respondent's age and gender.

## 4.4 Socio-cultural preferences and contextual impediments

The analysis of anecdotal responses indicates that behavioural adaptation among the respondents is affected by several non-thermal factors such as security, privacy, environmental nuisances (dust, noise and odour) and insects or animals menace (mosquitoes, monkeys, rats, lizards). Use of doors, windows and curtains was inhibited by security, environmental nuisances and privacy concerns, whereas noise and maintenance were the key concerns restricting the use of exhaust fans. Ceiling fan usage reported no significant barriers since it is a cost–effective adaptation measure for hot and humid environments with no associated socio-cultural constraint. Most occupants did not report visual reasons as interferences to environmental controls indicating apathetic attitude towards visual comfort. Spatial configuration, temporal factors and underlying societal norms also influenced the thermal adaptation behaviour. For instance, some of the households did not exercise window opening control because windows were either obstructed by furniture or permanently covered in need of additional storage space. (Fig. 14). The major factor restricting air-conditioner usage was energy cost burden which made it unaffordable for the LIG occupants to use it regularly. The non-working female respondents stated that air-conditioners were operated in summers typically at night in presence of the male member which reflected patriarchal societal norms. Air-conditioners were limited to only 9% of samples and hence generalization of results may not be feasible, however similar inferences were drawn by Bardhan et al. [38] while studying the gender power dynamics within low-income housing. Clothing adaptation was primarily hindered by the gendered socio-cultural practice of *purdah* system and western influences rather than thermal needs. The *purdah* system also influenced the decision of opening/closing of the curtains.

Figure 14: Window openings blocked by furniture and storage (Source: Authors).

The barriers to thermal adaptation were further analyzed to understand differences within the contextual settings of neighbourhoods.  Figure 15 presents a comparison of the reported impediments to behavioural adaptation among the surveyed locations). Environmental nuisances, animal/insect menace, and security were the key barriers for respondents of L1. Other issues such as inaccessible windows, maintenance and repair cost of mechanical devices (exhaust fans, evaporative coolers), inefficiency of controls was also reported. On the contrary, respondents of L2 reported significantly lesser security constraints. Privacy was the major impediment for respondents residing in L2 followed by animal/insect menace and environmental nuisances.

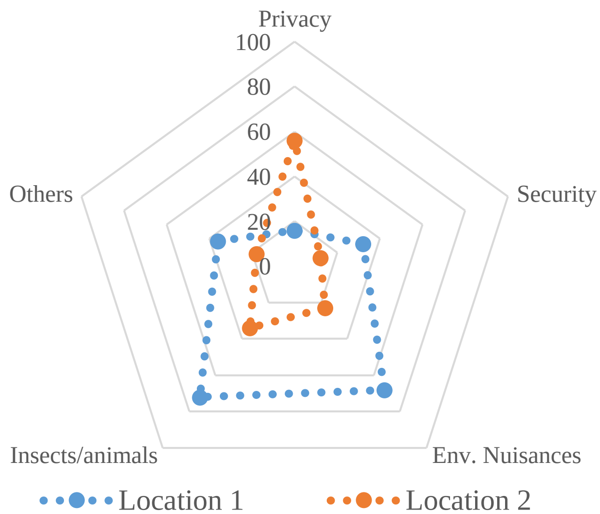


Figure 15: Locational differences in impediments to behavioural adaptation.

Significant differences among the neighbourhoods are attributed to a difference in their contextual characteristics. L1 residents had lesser privacy concerns while opening doors, windows or curtains possibly because they live as a community within neighbourhood. LI residents have been collectively relocated from a slum site and thus live in social cohesion. The circulation spaces i.e. external corridors, onto which the doors/ windows open, are characterised as lively and vibrant social interaction spaces in L1 (See Fig. 16a). Whereas in L2, the common circulation spaces are rather dull and quiet with limited interaction among the neighbours. This is further supported by the observation that residents of L1 kept their doors open 94% of the time while those of L2 opened it for 62% of the time. However, no significant differences in windows opening frequency were found among the two locations. L2 residents have the advantage of being located in a restricted premise and therefore faced lesser security concerns. Further, environmental nuisances in form of noise, dust or odour were also minimum within the lush green campus. In contrast, the dense urban form of L2 is characterized as filthy with foul smell due to poor maintenance by the local authorities

(Fig. 16b). Additionally, being located in close proximity to the arterial roads lead to traffic noise and disturbances.

Figure 16: Built environment characteristics of location 1 (L1) a) Corridors treated as extended living spaces b) poor maintenance of common areas (Source: Authors).

## 4.5 Quantifying the use of behavioural controls: Logistic regression models

Representing occupants’ behavioural controls in mathematical models would enable the use of these models in building performance simulation to evaluate the influence of occupant behaviour on building performance and thus to inform building design and operation. Such models are also important for energy analysis and evaluating the relationship between comfort and energy use. This subsection focusses on quantifying environmental control actions by applying logistic regression to develop adaptive algorithms. Logistic regression is a well-established statistical technique in thermal comfort research for predicting the probability of exercising an environmental control with respect to thermal environment variables [39,40]. This method is best suited for binary outcome variables and does not impose the assumption of normality of errors. Logistic regression involves calculating the logit function which is given by:

$$\text{logit}\ (p) = \log\ (p/\ (1-p)) = bS+c$$

Where p is the probability of use of environmental control, S is the thermal stimuli, b is the coefficient for thermal stimuli and c is the constant. The probability function is calculated using the following equation:

$$p=e^{(bS+c)}/(1+e^{(bS+c)})$$

Logistic regression analysis was carried out using IBM SPSS Statistics v26 to obtain adaptive algorithms based on maximum likelihood estimation. The Nagelkerke R Square value was used as a measure for goodness of fit. The proportion of usage of controls using binary data (on/open=1, off/closed=0) was analysed with respect to thermal stimuli (temperature, relative humidity). To improve the predictive power of adaptive algorithms, multivariate logistic regression was applied in certain cases. However, strongly correlated variables such as outdoor temperature and indoor temperature or indoor and outdoor Rh were not considered simultaneously to avoid any errors. The external door algorithm yielded insignificant results and was excluded from further investigation. The insignificant results for external doors was attributed to the fact that door opening was primarily driven by non-thermal factors. The logistic regression equations and predictive curves for windows, ceiling fans, exhaust fans and curtains are shown in Table 6 and Figure 17 respectively.

Table 6: Logistic regression results for different environmental controls.

| Control | No. of obs. | Algorithm ($p<0.001$) | Predictors | Nagelkerke R square |
|---|---|---|---|---|
| Windows | 705 | Logit(*pwin*) = 0.02 $Rh$ -0.85 | Indoor relative humidity, $Rh$ | 0.02 |
| Ceiling fans | 705 | Logit(*pcf*) = 0.44$T_g$+0.08$Rh$ -17.29 | Indoor globe temperature, $T_g$<br>Indoor relative humidity, $Rh$ | 0.42 |
| Exhaust fans | 230 | Logit(*pef*) = 0.08 $Rh$ -8.16 | Indoor relative humidity, $Rh$ | 0.15 |
| Curtains | 365 | Logit(*pcurt*) = 0.15$T_g$-4.58 | Indoor globe temperature, $T_g$ | 0.03 |

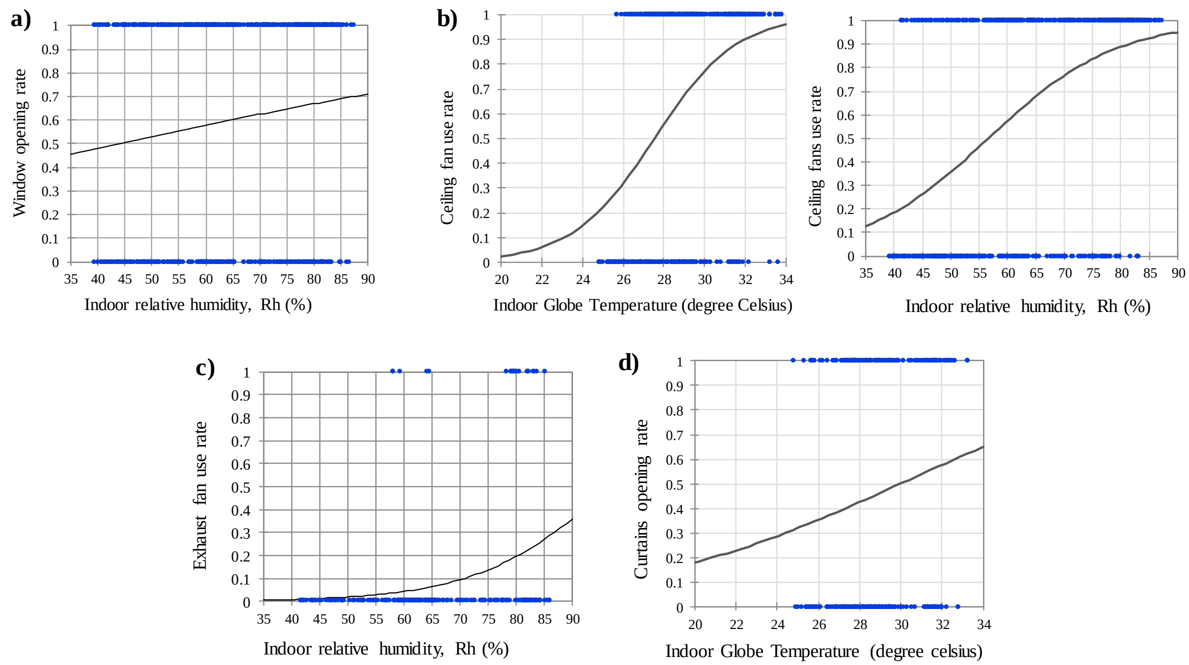


Figure 17: Logistic regression curves for a) Windows b) Ceiling fans c) Exhaust fans and d) Curtains in relation to thermal stimuli.

*Windows*

The probability of opening windows, *pwin* as a function of relative humidity, $Rh$ was observed to be statistically significant but with a small $R_2$ value of 0.02. A possible explanation for the low $R_2$ value is that the thermal stimuli alone may not explain the variations of probabilities [39]. As far as our knowledge, no study has quantified the effect of humidity on environmental controls and thus no comparative evidences could be found. The logistic curve presented in Figure 17a informs us that there is a 64% probability that LIG occupants will open windows at 70% $Rh$ level (upper limit of ideal humidity ranges as prescribed by ASHRAE). The horizontal structure of the curve depicts the presence of non-thermal factors in window opening behaviour. Indoor or outdoor temperature did not prove to be good predictors of window opening which is contrary to the findings from previous works. This could possibly be because of two main reasons. Firstly, indoor humidity being the major cause of discomfort within the subject dwellings than temperature and secondly, prioritization of other controls such as ceiling fans usage at high temperatures over window opening due to associated contextual constraints.

*Ceiling fans*

Multivariate logistic regression of ceiling fan usage with respect to indoor globe temperature $T_g$ and indoor relative humidity, $Rh$ yielded significant results with a high proportion of deviance ($R^2$ =0.42, p<0.001). A relatively higher $R^2$ value for ceiling fan logistic model as compared to other environmental controls ascertains the lesser role of non-thermal factors in adoption of adaptive control. The regression coefficient of 0.44 with $T_g$ indicates sharp sensitivity of ceiling fan use in relation to $T_g$. The predictive curve revealed that $pcf$ was 50% at 27.5°C, while the probability increased to 90% at 32 °C. Indraganti et al. in their study within naturally ventilated offices located in warm humid climate observed similar results with 50% $pcf$ at around 28°C [41]. $Rh$ showed lower sensitivity to changes than $T_g$ and the $pcf$ at 70% humidity was observed to be 76%.

*Exhaust fans*

Logistic regression yielded a significant and robust relationship of exhaust fan usage with $Rh$ ($R^2$=0.15, p<0.001). Resultant curve indicates that no exhaust fans were in use below 50% humidity levels and there was a steep rise in $pef$ above 70% Rh values. When compared to window opening model (Fig 17a), exhaust fan usage has a marginally lower probability of usage owing to limited ownership and restricted usage.

*Curtains*

Globe temperature was observed to be the thermal stimuli triggering action on curtains by low-income dwellers. Univariate logistic regression yielded significant p-value (p<0.001) but a low $R^2$ value of 0.03 indicating thermal environment may not be the sole predictor of operating curtain. This is supported by findings from anecdotal responses suggesting privacy and contextual factors affecting the use of curtains. The resultant curves demonstrate that there is a 50% probability of opening curtains at a globe temperature of 30°C.

Logistic regression curves have been used by researchers in determining the order of prioritization of controls [39]. However, it is not suitable to deduce such patterns for the present study since the availability of environmental controls across the population is not uniform. Moreover, a detailed investigation of the combined effect of temperature and humidity is required to understand the sequence of actions adopted by the occupants.

## 5 Discussion

Adaptive comfort behaviour in low-income housing is influenced by complexities of socio-cultural conformities, contextual settings, lifestyle practices coupled with affordability challenges. The results from the longitudinal survey in Indian low-income housing suggest that occupants do not fully exercise the adaptive opportunity available to them in response to the thermal conditions. Behavioural adaptation patterns relating to the use of environmental controls indicate a higher significance of relative humidity than the widely accepted temperature variable. Further, the patterns reveal that impediments associated with environmental controls restrict the adaptive opportunity which may lead to compromised thermal environments. For instance, ceiling fans, reported no associated constraints, have a robust usage pattern with respect to environmental variables whereas external doors or windows, with stated constraints of privacy, security or environmental nuisances, have a rather unclear trend. Non-thermal aspects in form of built-environment characteristics, rigid socio-cultural norms and contextual settings were identified as the key influencing factors on behavioural adaptation in low-income housing. The study further revealed that it was difficult to quantify and predict comfort-related occupant behaviour owing to the presence of stochastic non-thermal factors. However, insights related to predictors and sensitivity were established from the resultant probability curves as discussed in Section 4.5.

The findings also give an indication about high thermal tolerance of low-income occupants which could be attributed to their altered expectations due to resource constraints or habituation to high temperature and humidity levels. The results from the present study when compared to other Indian studies investigating occupant comfort behaviour in relatively higher income groups reveal stark differences. For instance, Indraganti et al. and Rajasekar et al. witnessed that Hyderabad & Chennai residents actively adopt clothing insulation as an adaptation mechanism unlike LIG occupants of Mumbai which often trade-off their adaptive clothing opportunity for cultural conformities or social norms [7,42]. Contrasting evidences in window and door opening behaviour with respect to outdoor temperature were also observed [4]. Factors reflecting the underlying contextual and socio-cultural practices across India such as restricted clothing adaptation by females, impediments related to environmental nuisances etc. were common among the present study and the similar studies in existing literature. However, the effect of these factors on thermal adaptation seems to be higher in the present study.

Various policy initiatives such as Housing for All 2022 and Slum Rehabilitation Scheme have been undertaken by the Government of India to provide better housing opportunities to low-income population. The policy implications from this study could be through the development of design guidelines for the housing schemes to create thermally comfortable LIG dwellings. With more than 12 million affordable housing units to be built in India, this work would enable the architects and designers to provide a sustainable built environment through the integration of socio-cultural practices into the building design. This study would also help improve occupant behaviour models for building performance simulation to better predict comfort levels and energy use in LIG households. Low-income population may not be a significant contributor to the energy burden in the present times but with increase in disposable income and rapid advances in technology, it is expected that the household energy consumption patterns would change substantially [43]. Indian residential sector has witnessed a steep decadal growth in room AC sales from 2 million to 30 million [44] with a positive correlation to household income [45] hinting towards future rebound effects and an increase in cooling demand. It is therefore of utmost importance to provide pragmatic adaptation measures which could be adopted by low-income occupants without conflicting with the prevalent socio-cultural and economic construct of comfort.

Future efforts may include a combined analysis of occupants' behavioural and physiological adaptation for a better comprehension of thermal comfort preferences. One of the limitations of this study was that the effect of group negotiations on use of environmental controls within the household was not accounted. The other limitation was that thermal history of the respondents, which may influence the perception of comfort, was not considered here.

## 6 Conclusion

This paper presents a thermal comfort and occupant behaviour study conducted for the first time in free-running low-income urban housing of Mumbai, India. 705 set of responses along with simultaneous indoor environment measurements were gathered to investigate patterns of adaptive comfort behaviour and the associated non- thermal drivers. The results highlight the dominance of socio-cultural regimes, built environmental characteristics and economic capabilities on occupants' behavioural adaptation. The major outcomes derived from the field study analysis are:

- Proportion of open windows and doors was strongly correlated with indoor relative humidity (Rh) than the outdoor and indoor temperature variables. Ceiling fan usage correlated strongly with indoor environment variables (globe temperature and indoor relative humidity) than outdoor temperature. Exhaust fan usage was sensitive to changes in indoor relative humidity and a gradual increase in proportion of use was observed as the Rh levels increased from 50% to 90%.
- Proportion of use of artificial lights relating to time of the day revealed that though the lights were used throughout the day, the usage was least in late afternoon hours. Additionally, the comparison of curves for proportion of lights and curtains in use indicated an inverse quadratic trend.

- Spatial configuration, temporal factors and underlying societal norms influenced the thermal adaptation behaviour in low-income housing. Significant variations in adaptive comfort behaviour were observed among the surveyed neighbourhoods owing to the different contextual characteristics. Clothing adaptation was primarily hindered by the gendered socio-cultural practice of *purdah* system and western influences rather than thermal needs.
- Logistic regression technique was applied to predict the probability of occupants' environmental control actions (windows, fans and curtains). The resultant curves characterised occupant actions as a function of indoor relative humidity and globe temperature. Additionally, the regression results exhibited low $R_2$ values suggesting that thermal stimuli alone cannot predict occupant behaviour due to the presence of non-thermal drivers.

In summary, this study provides interesting insights to the adaptive comfort behaviour in LIG housing where non-thermal determinants often govern occupants' actions. This work would enable the policymakers, housing boards and architects in providing adequate thermal environment within low-income housing thereby delivering better housing solutions for the vulnerable population.

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## References


[1] B. Dean, J. Dulac, K. Petrichenko, P. Graham, Global Status Report 2016: Towards zero-emission efficient and resilient buildings, 2016. https://wedocs.unep.org/rest/bitstreams/45611/retrieve.

[2] Energy Efficiency in Buildings: Transforming the market, 2009. doi:10.1108/EUM0000000002227.

[3] J. Malik, R. Bardhan, Energy target pinch analysis for optimising thermal comfort in low-income dwellings, J. Build. Eng. 28 (2020). doi:10.1016/j.jobe.2019.101045.

[4] M. Indraganti, Behavioural adaptation and the use of environmental controls in summer for thermal comfort in apartments in India, Energy Build. 42 (2010) 1019–1025. doi:10.1016/j.enbuild.2010.01.014.

[5] G.S. Brager, R.J. De Dear, Thermal adaptation in the built environment : a literature review, Energy Build. 1 (1998) 83–96. doi:10.1016/S0378-7788(97)00053-4.

[6] R.L. Hwang, M.J. Cheng, T.P. Lin, M.C. Ho, Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal comfort and energy saving in hot-humid regions, Build. Environ. 44 (2009) 1128–1134. doi:10.1016/j.buildenv.2008.08.001.

[7] M. Indraganti, Thermal comfort in apartments in India: Adaptive use of environmental controls and hindrances, Renew. Energy. 36 (2011) 1182–1189. doi:10.1016/j.renene.2010.10.002.

[8] T. Kubota, H. Bahadur, R. Hiroto, Sustainable Houses and Living in the Hot-Humid Climates of Asia, Springer, 2018. doi:10.1007/978-981-10-8465-2.

[9] J. Kim, R. de Dear, T. Parkinson, C. Candido, Understanding patterns of adaptive comfort behaviour in the Sydney mixed-mode residential context, Energy Build. 141 (2017) 274–283. doi:10.1016/j.enbuild.2017.02.061.

[10] Y. Song, Y. Sun, S. Luo, Z. Tian, J. Hou, J. Kim, T. Parkinson, R. de Dear, Residential adaptive comfort in a humid continental climate – Tianjin China, Energy Build. 170 (2018) 115–121. doi:10.1016/j.enbuild.2018.03.083.

[11] M.J. Sorgato, A.P. Melo, R. Lamberts, The effect of window opening ventilation control on residential building energy consumption, Energy Build. 133 (2016) 1–13. doi:10.1016/j.enbuild.2016.09.059.

[12] H. Feriadi, N.H. Wong, Thermal comfort for naturally ventilated houses in Indonesia, Energy Build. 36 (2004) 614–626. doi:10.1016/j.enbuild.2004.01.011.

[13] C. Sánchez-Guevara Sánchez, A. Mavrogianni, F.J. Neila González, On the minimal thermal habitability conditions in low income dwellings in Spain for a new definition of fuel poverty, Build. Environ. 114 (2017) 344–356. doi:10.1016/j.buildenv.2016.12.029.

[14] T. Moore, I. Ridley, Y. Strengers, C. Maller, R. Horne, Dwelling performance and adaptive summer comfort in low-income Australian households, Build. Res. Inf. 45 (2017) 443–456. doi:10.1080/09613218.2016.1139906.

[15] A. Pérez-Fargallo, J.A. Pulido-Arcas, C. Rubio-Bellido, M. Trebilcock, B. Piderit, S. Attia, Development of a new adaptive comfort model for low income housing in the central-south of chile, Energy Build. 178 (2018) 94–106.

doi:10.1016/j.enbuild.2018.08.030.

[16] M.C.G.M., Mumbai DRMMP, 2011. http://dm.mcgm.gov.in:9080/gmdma/wp-content/uploads/2015/pdf/city_profile.pdf.

[17] Bureau of Energy Efficiency, Design guidelines for energy-efficient multi-storey buildings - warm and humid climates, 2016. http://www.beepindia.org/sites/default/files/resources/Residential Guidelines_Warm-Humid Climates.pdf.

[18] Weather Underground, (2019). https://www.wunderground.com/weather/in/mumbai (accessed May 16, 2019).

[19] R. Bardhan, R. Debnath, A. Jana, L.K. Norford, Investigating the association of healthcare-seeking behavior with the freshness of indoor spaces in low-income tenement housing in Mumbai, Habitat Int. 71 (2018) 156–168. doi:10.1016/j.habitatint.2017.12.007.

[20] J. Lueker, R. Bardhan, A. Sarkar, L. Norford, Indoor air quality among Mumbai's resettled populations: Comparing dharavi slum to nearby rehabilitation sites, Build. Environ. (2019). doi:10.1016/j.buildenv.2019.106419.

[21] R. Bardhan, M. Sunikka-blank, A. Nasra, Sentiment analysis as tool for gender mainstreaming in slum rehabilitation housing management in Mumbai , India, Habitat Int. (2019) 102040. doi:10.1016/j.habitatint.2019.102040.

[22] R. Bardhan, S. Sarkar, A. Jana, N.R. Velaga, Mumbai slums since independence: Evaluating the policy outcomes, Habitat Int. 50 (2015) 1–11. doi:10.1016/j.habitatint.2015.07.009.

[23] J. Nijman, Against the odds: Slum rehabilitation in neoliberal Mumbai, Cities. 25 (2008) 73–85. doi:10.1016/j.cities.2008.01.003.

[24] ASHRAE-55, Thermal Environmental Conditions for Human Occupancy, 2017.

[25] International Organization for Standardization, ISO 8996:2004 Ergonomics of the thermal environment -- Determination of metabolic rate, 2004.

[26] Testo GmbH & Co., Lenzkirch, Germany, (n.d.). https://www.testo.com/en-IN/testo-480/p/0563-4800 (accessed December 12, 2019).

[27] J.F. Nicol, M.A. Humphreys, S. Roaf, Adaptive Thermal Comfort Principles and Practice, Routledge, 2012.

[28] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy Build. 34 (2002) 563–572. doi:10.1016/S0378-7788(02)00006-3.

[29] J. Liu, R. Yao, R. McCloy, An investigation of thermal comfort adaptation behaviour in office buildings in the UK, Indoor Built Environ. 23 (2014) 675–691. doi:10.1177/1420326X13481048.

[30] J.F. Nicol, Characterising occupant behaviour in buildings: Towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans, in: Seventh Int. IBPSA Conf., 2001: pp. 1073–1078.

[31] J.F. Nicol, M.A. Humphreys, B. Olesen, A stochastic approach to thermal comfort - Occupant behavior and energy use in buildings, ASHRAE Trans. 110 PART I (2004) 554–568.

[32] I.A. Raja, J.F. Nicol, K.J. McCartney, M.A. Humphreys, Thermal comfort: Use of controls in naturally ventilated buildings, Energy Build. 33 (2001) 235–244. doi:10.1016/S0378-7788(00)00087-6.

[33] J.K. Nayak, J.A. Prajapati, Handbook on Energy Conscious Buildings, Indian Institute of Technology Bombay and Solar Energy Centre, Ministry of Non-conventional Energy Sources, Government of India, 2006. http://xlink.rsc.org/?DOI=C5EE01283J.

[34] A. Khurshid, P. Shah, Claiming modernity through clothing: gender and education in Pakistani Muslim and Indian Hindu communities, Gend. Educ. 31 (2019) 189–204. doi:10.1080/09540253.2017.1302077.

[35] W. Yang, G. Zhang, Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China, Int. J. Biometeorol. 52 (2008) 385–398. doi:10.1007/s00484-007-0133-4.

[36] B. Cao, Y. Zhu, Q. Ouyang, X. Zhou, L. Huang, Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing, Energy Build. 43 (2011) 1051–1056. doi:10.1016/j.enbuild.2010.09.025.

[37] A.K. Mishra, M. Ramgopal, Field studies on human thermal comfort - An overview, Build. Environ. 64 (2013) 94–106. doi:10.1016/j.buildenv.2013.02.015.

[38] M. Sunikka-blank, R. Bardhan, A. Nasra, Gender , domestic energy and design of inclusive low-income habitats : A case of slum rehabilitation housing in Mumbai , India, Energy Res. Soc. Sci. 49 (2019) 53–67. doi:10.1016/j.erss.2018.10.020.

[39] F. Haldi, D. Robinson, On the behaviour and adaptation of office occupants, Build. Environ. 43 (2008) 2163–2177. doi:10.1016/j.buildenv.2008.01.003.

[40] H.B. Rijal, P. Tuohy, F. Nicol, M.A. Humphreys, A. Samuel, J. Clarke, Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings, J. Build. Perform. Simul. 1 (2008) 17–30. doi:10.1080/19401490701868448.

[41] M. Indraganti, R. Ooka, H.B. Rijal, Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender, Energy Build. 103 (2015) 284–295. doi:10.1016/j.enbuild.2015.05.042.

[42] E. Rajasekar, A. Ramachandraiah, Adaptive comfort and thermal expectations–a subjective evaluation in hot humid climate, in: Adapt. to Chang. New Think. Comf., 2010: p. 18. http://nceub.commoncense.info/uploads/48-01-17-Rajasekar.pdf.

[43] J. Malik, R. Bardhan, P. Banerji, Rethinking Indoor Thermal Comfort in the Era of Rebound & Pre-bound Effect for the Developing World: A Systematic Review, Indoor Air. (2020). doi:10.1111/INA.12664.

[44] TERI, NRDC, IGSD, Improving Air Conditioners in India, 2018.

[45] A. Phadke, N. Abhyankar, N. Shah, Avoiding 100 New Power Plants by Increasing Efficiency of Room Air Conditioners in India : Opportunities and Challenges, in: 7th Int. Conf. Energy Effic. Domest. Appliances Light., 2013: pp. 1–14. https://ies.lbl.gov/sites/default/files/lbnl-6674e.pdf.

[46] G. Havenith, Y. Ouzzahra, K. Kuklane, K. Lundgren, J. Fan, Y. Au, S. Hodder, D. Loveday, A Database of Static Clothing Thermal Insulation and Vapor Permeability

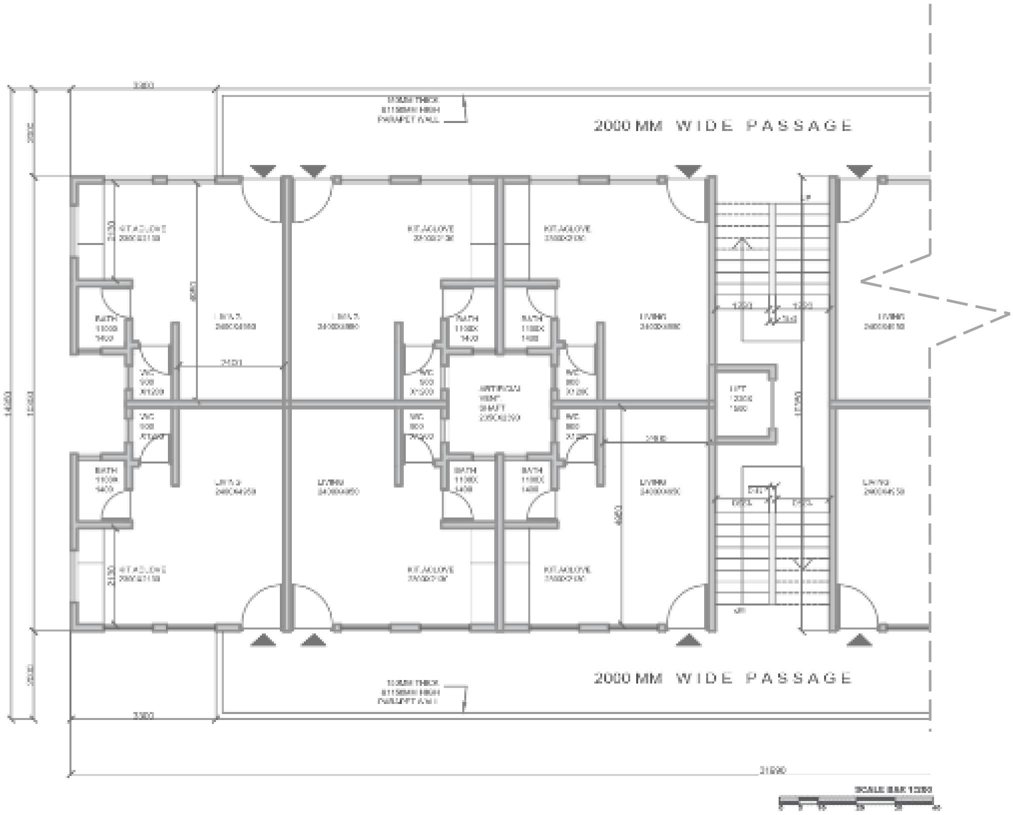
Values of Non-Western Ensembles for Use in ASHRAE Standard 55, ISO 7730, and ISO 9920, ASHRAE Trans. 121 (2015) 197–215.

[47] M. Indraganti, J. Lee, H. Zhang, E.A. Arens, Thermal adaptation and insulation opportunities provided by different drapes of Indian saris, Archit. Sci. Rev. 58 (2015) 87–92. doi:10.1080/00038628.2014.976540.

[48] R. Rawal, S. Manu, Y. Shukla, L.E. Thomas, R. de Dear, Clothing insulation as a behavioural adaptation for thermal comfort in Indian office buildings, Proc. 9th Wind. Conf. Mak. Comf. Relev. (2016).

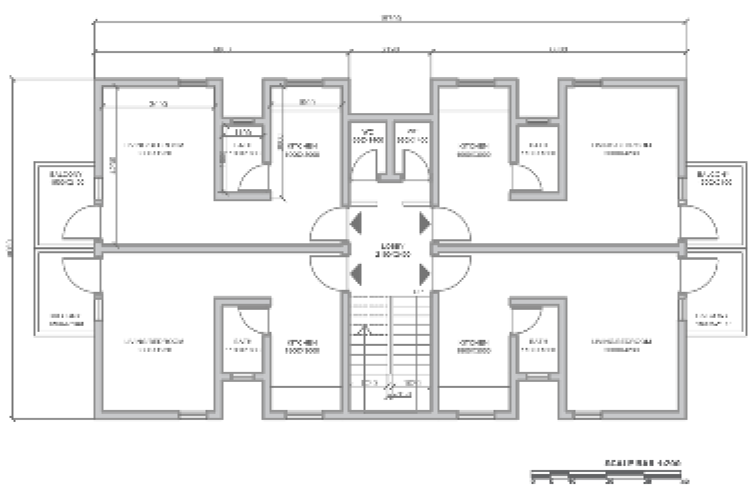
[49] Ministry of Housing & Urban Poverty Alleviation Government of India, Pradhan Mantri Awas Yojana - Housing for All (Urban) - Scheme Guidelines 2015, (2015) 1–62. http://mhupa.gov.in/pmay/repository/01_PMAY_Guidelines_English.pdf.

**Appendix A: Floor Plans**




**Typical Floor Plan**
**Location 1**

*Typical Unit Size: 22.3 sq.m*



**Typical Floor Plan**
**Location 2**

*Typical Unit Size: 26.2 sq.m*

**Appendix B: Clothing insulation values for Indian garments**

| Clothing Type | Clothing insulation, $I_{cl}$ (clo) | Reference |
|---|---|---|
| **Ensemble** | | |
| Burqa with hijaab | 1.33 | G. Havenith et al., 2015 [46] |
| Salwar kameez (cotton) | 0.58 | |
| Salwar kameez (polyester) | 0.74 | |
| Sari (cotton) | 0.65 | M. Indraganti, J. Lee, H. Zhang, and E. A. Arens, 2015 [47] |
| Sari (polyester) | 0.74 | |
| **Garment** | | |
| Long gown | 0.3 | ASHRAE Standard 55-2017 [24] |
| Trousers | 0.2 | |
| Jeans | 3 | |
| Long sleeve Shirt/blouse (polyester) | 0.3 | |
| Long sleeve Shirt/blouse (cotton) | 0.25 | |
| Short sleeve Shirt/blouse (polyester) | 0.24 | |
| Short sleeve Shirt/blouse (cotton) | 0.19 | |
| T-shirt | 0.19 | |
| Jacket/woolen Jacket | 0.4 | |
| Cardigan/pullover/Sweater | 0.3 | |
| Dhoti/petticoat | 0.15 | R. Rawal, S. Manu, Y. Shukla, L. E. Thomas, and R. de Dear, 2016 [48] |
| Shorts | 0.13 | |
| Skirts | 0.19 | |
| Vest | 0.06 | |
| Hijaab | 0.1 | |
| Shawl | 0.3 | |
| Dupatta | 0.08 | |
| **Inner wear** | | |
| Bra | 0.01 | ASHRAE Standard 55-2017 [24] |
| Panties | 0.03 | |
| Men's Brief | 0.04 | |
| **Seating** | | |
| Plastic moulded /wooden/metal chair | 0 | ASHRAE Standard 55-2017 [24] |
| Plastic moulded wooden/metal chair used with a cushion for seat | 0.15 | |
| Bed/sofa | 0.15 | R. Rawal, S. Manu, Y. Shukla, L. E. Thomas, and R. de Dear, 2016 [48] |